Human Factors
Boeing Wichita

A Comparison of Sinusoidal and Random Vibration Effects on Human Performance

Technical Report D3-3512-2
Contract NONR 2994(00)
Office of Naval Research

AD-261331

Technical Report No. 2

A COMPARISON OF SINUSOIDAL AND RANDOM VIBRATION EFFECTS ON HUMAN PERFORMANCE

Research Accomplished Under
Office of Naval Research
Contract Nonr 2994(00)
"Research On
Low Frequency Vibration Effects
On Human Performance"

By

Donald L. Parks
HUMAN FACTORS UNIT

Principal Investigator
J. E. Beaupeurt

THE BOEING COMPANY
Wichita Division

D3-3512-2 28 July 1961

ABSTRACT

Ten male subjects performed a complex task during vertical vibration in a preliminary study to compare performance with sinusoidal, constant period random amplitude, and random (aircraft turbulence) vibration. Performance on the three subtasks varied: performance on a tracking task with delayed control-display feedback was differently affected according to type of vibration; no affect was found for a tracking task without feedback delay; and response time did not change.

Results were analyzed for consistent trends in vibration effects which could be correlated with mechanical and psychological definitions of vibration for evidence of a human performance transfer function for vibration. Psychological and amplitude bases for this function could not be found, vibration acceleration (g) effects were not clear, and RMS amplitude power was correlated with constancies in performance. It was suggested that testing combinations of RMS and frequency (and related factors) could lead to a performance transfer function permitting transformation of human performance data from sinusoidal to operational vibrating environments.

Document Number D3-3512-2 reports the second experiment of a series designed to study vibration effects on human performance. Other experiments will be reported sequentially in the document series D3-3512-1 through D3-3512-7. All results will be integrated and summarized in D3-3512-0.

Test Design & Conduct Donald L. Parks
D. L. Parks

Report Donald L. Parks
D. L. Parks

Supervised F. W. Snyder
F. W. Snyder

Approved J. E. Beaupeurt
J. E. Beaupeurt
Unit Chief

Approved
Subsection Chief

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

REFERENCES

a. Boeing Document D3-3512-1, "Human Reaction to Low Frequency Vibration, D. L. Parks, 2 December 1960

b. Boeing Document D3-3301, "Boeing Human Vibration Facility," 23 September 1960

c. Boeing Document D3-1189, "Preliminary Study of Aircrew Tolerance to Low Frequency Vertical Vibration," R. B. Gorrill and F. W. Snyder, 3 July 1957.

d. Design and Analysis of Experiments in Psychology and Education, 1956, The Riverside Press, Mass.

e. Experimental Design in Psychological Research, 1953, Allen L. Edwards, Rinehart & Co., Inc., New York.

INTRODUCTION

Sinusoidal vibration has been known to affect human performance and resulting man-machine capability for some time (reference 6). Analysis of the problem suggests that at least two design considerations could be used effectively to optimize human performance: (1) proper display-control selection, and (b) air frame design to control effects of vibration on human capability. However, the quantity of data available for these decisions is limited. That data which is available must be applied with reservation since it was derived under conditions of sinusoidal vibration. No way to adequately relate such data to operational conditions in the form of conversion factors has been determined, although it is strongly suspected that a common relationship between the two does exist.

Since proper conversion factors relating human information for sinusoidal and random vibration environments are not known, the current state of the art offers two approaches to design decisions pertinent to expected human performance during vibration. One approach is to apply data derived during sinusoidal vibration, not knowing how interactions of frequency and amplitude may affect performance. The other is to simulate the vibration expected for each new equipment design and derive appropriate performance measures. Actually, neither of these approaches is considered an adequate solution to design problems. The reservations that must be attached to the first can seriously affect optimum design of a man-machine system. The second approach is economically undesirable since performance tests with a new vibration environment for each new vehicle would be required. A conversion factor would permit the transforming of human performance data from one vibration environment to another. This would lead to more efficient data collection with sinusoidal vibration and direct application of the results to any defined random vibration environment.

This study was designed to explore another possibility, using both sinusoidal and random vibration, to seek relationships that could eventually result in definition of a conversion factor for human performance from sinusoidal to random vibration. Several conditions were defined for which vibration could be equated on selected bases, and an interim vibration (constant period random amplitude vibration) was added between the sinusoidal and operational vibration environments, from the hypothesis that it could help clarify parallel trends. If trends toward consistent performance could be found for any of these vibration conditions, a study program oriented toward identifying performance conversion factors (or a transfer function) could be more clearly defined. The preliminary data reported here would also promote a clearer understanding of the reservations that must be attached to use of available data.

The bases for equating or comparing vibration in this study included:

1. Representative subjective judgment of vibration severity (reference a).

2. Equal mean amplitude.

3. Equal root mean square (RMS) amplitude power (equal to selected portions of the power spectral density (PSD) curves describing aircraft vibration).

4. Differing amplitudes for the same vibration wave form.

Full recognition was given the fact that the complex experimental design used, combined with the relatively small amount of data collection possible, could lead to difficulties in adequate statistical analysis. However, it was anticipated that sufficient data would be collected to determine trends in performance changes and to adequately analyze the variables for a more sophisticated study.

SUMMARY

A preliminary experiment was conducted in the Boeing human vibration facility to examine the correlation, if any, between certain physical descriptions of vertical vibration and comparability of human performance data. It was logical to suspect the existence of some factor which would permit extrapolations of expected performance from one vibration environment to another. This experiment serves as a preliminary step in determining the possibility of a transfer function for such applications.

A power spectral density (PSD) description of vibration was used to simulate vertical aircraft turbulence in the vibration facility. Those frequencies found to have the most relative power in the PSD function were selected as most apt to affect performance on the basis of having the greatest amount of recurring acceleration, and most apt to permit comparisons of performance from sinusoidal to PSD vibration. The frequencies selected, 0.75 cps and 2.5 cps, defined the number of repetitions per second (or the period) for sinusoidal and random amplitude vibration conditions to be used in this test.

The three vibration conditions selected permitted study of performance with vibration equated according to (a) equal root mean square (RMS) amplitude power; (b) subjective equality; or (c) equal mean amplitude. Of the comparisons provided with this selection only RMS could be described as a physical parameter with comparable effects on human performance for different vibration conditions, although other correlations could exist. Other comparisons resulted in significantly different performance capability between conditions which eliminated the particular condition as a potential basis for a transfer function. There is evidence to suggest that a mathematical function providing for an interaction of RMS amplitude power and frequency would significantly increase understanding of correlative factors and permit transferring data from one vibration environment to another.

A complex task consisting of three subtasks was performed by ten subjects during vibration for each experimental condition (PSD, 0.75, and 2.5 cps vibration). Only one subtask, which required the subjects to anticipate display position of control-display feedback delay, was differentially affected. A tracking task without feedback delays and with color coding was not differently affected by different vibration conditions, nor was the third task which measured response time. Hence there are questions to be answered about quantity and degree for a transfer function. Precision of the measures used may be an added significant variable in studying effects of vibration on the wide range of human perceptual-motor skills.

The large number of vibration frequencies and accelerations randomly present in an operational human environment puzzles systems designers trying to extrapolate and apply human capability data from the single frequency sinusoidal vibration used in laboratory studies. Engineers have discovered a way to perform this function for equipment but data leading to similar application of data for operators is nonexistent. The need for information of this nature led to this study to determine feasibility of similar transfer functions for human performance. A demonstration of feasibility could then open up a new area in the field of human vibration research and facilitate the best application of data by design engineers.

CONCLUSIONS

1. There is evidence that transfer functions will permit extrapolation of performance data from sinusoidal to random vibrating environments. From vibration conditions used in this study, equal RMS amplitude power equivalence is one possible physical description of vibration leading to a conversion factor for human performance capability. A mathematical combination of RMS and frequency is the most promising possibility from the tested conditions for comparisons of human performance.

2. Vertical vibration amplitude varied considerably at certain frequencies with relatively small effects on performance in terms of a transfer function.

3. More extensive testing of these and other task and vibration relationships is necessary to clearly define the correct physical basis for transforming data from one vibration environment to another. A wider frequency and amplitude range than used for this study is necessary with simple but precise performance measures known to have minimum variation between subjects since performance measures must be made with vibration as the only independent variable.

4. Transfer relationships may be found to differ for various perceptual-motor capabilities.

RECOMMENDATIONS

A program is required to define performance conversion factors for confident and accurate application of human vibration data to operational vibration environments. The research described here demonstrates the feasibility of the concept and the need for further study to accurately define a performance transfer function for vibration.

The feasibility of obtaining additional transfer functions for converting basic data from the ideal, nonvibrating environment to operational conditions also requires investigation.

METHODOLOGY

Definition: Power spectral density (PSD) as used here is a means of presenting the average (mean square) acceleration or amplitude for each vibration frequency occurring in a random vibration environment.

General

The vibration used for this test consisted of a random time history of vertical acceleration having certain statistical properties that are typical of the vertical accelerations experienced during low level flight. The properties of this vibration are described by the "power spectral density" (PSD) function of the vertical acceleration. A PSD was selected based on analysis and experience gained during extensive design and flight test experience. The selected power spectrum of acceleration was then converted to the equivalent power spectrum of vertical displacement in order to accommodate the type of hydraulic controls available on the vibration facility.

A random time history of displacement having the desired spectral properties was then obtained by using an analogue computer to properly filter the output of a "white noise" generator. This time history was recorded on magnetic tape to ensure equal vibration stimuli for the different subjects and the tape was used to operate the servo-valve control in the hydraulic-actuating mechanism. Thus the conclusions would not be confounded by different intensities experienced by different subjects for a given performance measure.

Figure 1 presents the selected acceleration power spectrum in comparison to the spectrum obtained from the white noise generator in terms of "g" (acceleration). The curves presented describe the PSD for this and for reference (a) tests. There was some evidence that the hydraulic-actuating system had a tendency to filter out some of the high frequency content of this spectrum although the resulting "playback" fidelity was 95 per cent or better.

Another input, a constant period random amplitude vibration, was derived through similar use of the computer for 0.75, then 2.5, cycles per second, corresponding to those frequencies with the strongest "power" in the PSD description.

Amplitude power of the taped series could be regulated by a simple gain adjustment. The third type of vibration (a sinusoidal wave form) was produced by a signal generator, which was set at 0.75, then 2.5 cycles, for individual tests. The vibration amplitude could be regulated by varying strength of the input signal.

Some of the vibration for this study was limited for the most precise comparisons by the present limit of ten inches vertical travel for the vibration platform so that the comparisons are really based on approximations to equivalent vertical vibration. Since this effected the 0.75 cycle portion of the curve only, and the net differences in displacement and accelerations were small, it could be assumed that any differences in effect would be negligible.

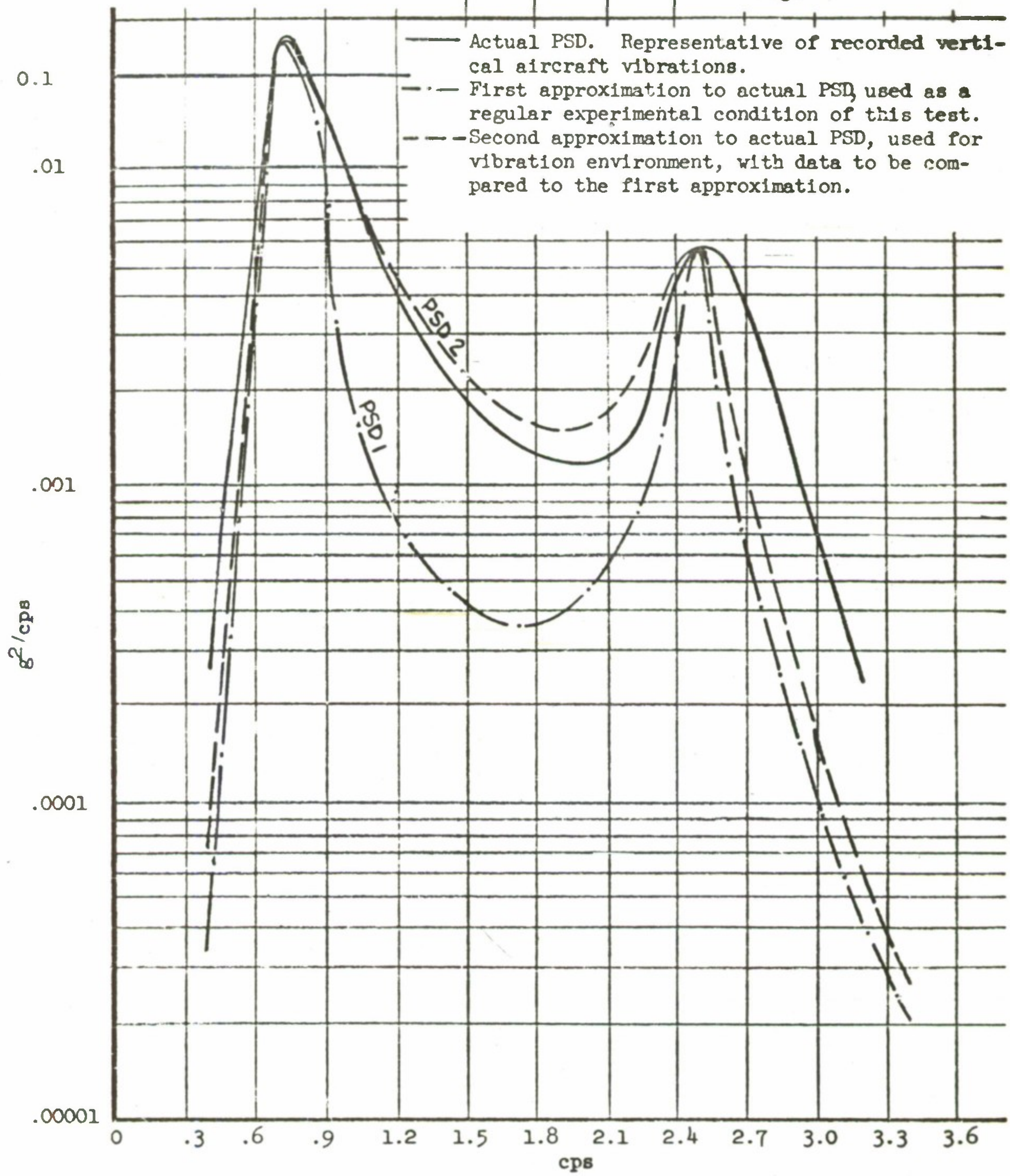


Figure 1. Power Spectral Density Curves Showing a Comparison Between the Aircraft PSD and the Approximations Used for Test Conditions

Table I defines the vibration variables and indicates those comparisons which could be readily made. RMS values recorded in the table are equivalent to the RMS from the PSD description. The test conditions defined in Table I were selected purposely to obtain the desired comparisons for trend analysis. In reviewing possible ways of obtaining the desired information, a Latin Square statistical model appeared to be most efficient for data collection and analysis since a wide variety of information was desired in a short time and some logical method of mixing the different experimental conditions to counterbalance varying effects was desirable. The Latin Square selected had the normal restriction (reference e), i.e., a condition did not occur twice at the same position in a sequential order. An added restriction for this test was that no sequence of two experimental conditions was repeated in the matrix, thus averting the possibility of a repetitive sequence influencing the results.

The Latin Square indicating the order of presentation per subject is presented in Table II. Since the sessions were too long for a full series on one day, data were collected during two sessions spaced one week apart. Data for the second PSD approximation (figure 1) was collected after all the Latin Square conditions were completed.

Subjects (Ss)

Ss were ten Boeing-Wichita employees who had volunteered for human vibration studies, had completed the first experiment (reference a) of a series of studies, and who had prior nonvibration experience on the task. The same conditions as in reference a apply here, e.g., Ss passed a comprehensive physical examination to qualify for testing; a brief examination was completed before and after each test; and two wire mesh contacts for an electrocardiograph (ECG) system were placed on the pectoral (chest) muscles and held in place during tests by wrapping the chest with an elastic bandage. A third ECG contact was placed behind the ear and held in place with collodian. All Ss wore flight coveralls and street shoes for the test.

Apparatus

The Boeing-Wichita human vibration facility (reference b) was used to provide the vibration environment for this test. A standard aircraft seat mounted to the platform was reinforced to ensure the most complete transmission of vibration to the subject. Reinforced plywood inserts covered with 3/4 inch hard felt were used in place of normal aircraft cushioning for three reasons in addition to ensuring complete transmission of vibration. One reason was to obtain baseline data under conditions that can be readily repeated for future comparative studies (such as a continuation of those described here or investigating a new seat design or cushion) with a more limited sample. Another was to permit direct

TABLE I

DEFINITION OF VIBRATION CONDITIONS USED
AND BASIS FOR COMPARISON

(Each column of checks indicates that performance can be compared on the basis indicated by the column heading. For example, conditions 2, 3 and 8 can be compared for approximately equal RMS at 0.75 cps, as can conditions 2, 6 and 9 for 2.5 cps.)

Experimental Vibration Condition	RMS Equivalent		Mean Displacement Approximately Equal		Subjectively Similar or Equal
	0.75 cps	2.5 cps	0.75 cps	2.5 cps	
1. ½ Amplitude PSD					
2. Full Amplitude PSD	X	X			
3. 0.75 cps, 4.26" Mean, Double Amplitude Random	X				
4. 0.75 cps, 1.7 RMS, Amplitude Random			X		
5. 2.5 cps, 2.16" Mean, Double Amplitude Random				X	
6. 2.5 cps, .09 RMS, Amplitude Random		X			
7. 0.75 cps, 1.57" Double Amplitude Sinusoidal					
8. 0.75 cps, 4.52" Double Amplitude Sinusoidal (1.6 RMS)	X		X		X
9. 2.5 cps, .26" Double Amplitude Sinusoidal (.09 RMS)		X			
10. 2.5 cps, 1.08" Double Amplitude				X	X

As indicated in the right hand column, all conditions are defined by double amplitude or RMS amplitude. Conditions 1 and 2 indicate PSD, 3-6 constant period random amplitude/conditions, and 7-10 sinusoidal conditions. Selection of these conditions was based on desired comparisons, indicated in remaining columns.

Full amplitude PSD refers to vibration as described by PSD 1 (Figure 1.). One-half amplitude PSD is the same condition with all amplitudes smaller by one-half. Conditions 3-6 are cyclic in nature, hence the term cps, but feature random amplitudes with means as identified. Since RMS also defines means, the associated mean amplitude is not indicated unless it is required for another type of comparison.

TABLE II

LATIN SQUARE PRESENTATION
OF TEST CONDITIONS

	DAYS									
	1					2				
ORDER	1	2	3	4	5	6	7	8	9	10
SUBJECT 1	1	2	3	4	5	6	7	8	9	10
2	2	4	1	6	3	8	5	10	7	9
3	3	1	5	2	7	4	9	6	10	8
4	4	6	2	8	1	10	3	9	5	7
5	5	3	7	1	9	2	10	4	8	6
6	6	8	4	10	2	9	1	7	3	5
7	7	5	9	3	10	1	8	2	6	4
8	8	10	6	9	4	7	2	5	1	3
9	9	7	10	5	8	3	6	1	4	2
10	10	9	8	7	6	5	4	3	2	1

The Latin Square, indicating the order of experimental vibration conditions under which S was required to perform. The entries within the matrix identify conditions which are defined below.

1. $\frac{1}{2}$ Amplitude PSD
2. Full Power PSD
3. 0.75 Period Random Amplitude, 4.26 Inches DA Maximum
4. 0.75 Period Random Amplitude, 1.7 RMS
5. 2.5 Period Random Amplitude, 2.16 Inches Maximum
6. 2.5 Period Random Amplitude, .09 RMS
7. 0.75 cps 1.57 Inch DA
8. 0.75 cps 1.6 RMS 4.52 Inches DA
9. 2.5 cps .09 RMS .26 Inch DA
10. 2.5 cps 1.08 Inch DA

between-subject comparisons of performance data throughout this program on the basis of specific vibration intensities at the seat. The third was to avoid introduction of data confounding by a seat with a complex vibration absorption pattern (reference c, page 17) responding differently to different Ss' weight.

Also on the platform were a large aircraft control column, wheel, and a special test display panel (figure 2). The display panel, mounted in front of the subject and control column on the platform, was sloped at an angle of 10 degrees from the perpendicular with the lower edge nearest S. The panel was approximately 28 inches in front of the subject with the central display located 10 degrees below the horizontal line of sight for an average individual (some variation in this relationship was introduced by different subject heights). The control column was modified by the addition of a cutoff switch on the left hand grasp and a thumb button on the right hand grasp. Releasing the cutoff switch would stop vibration immediately, while pressing the right thumb button would turn off signal lights on the panel display. Rotary movement of the control wheel required forces of 0 to 10 pounds for ± 65 degrees of movement. For control column fore and aft movement, the forces were 0 to 64 pounds for maximum forward displacement of $7\frac{1}{4}$ inches, and 0 to 84 pounds aft for $9\frac{1}{2}$ inches maximum displacement. The force increase was essentially linear up to the maximum column displacement with the increase in required force determined by a spring constant.

The display panel included three testing components (figure 2). The central display was an amber cathode ray tube (CRT) upon which a moving display (0.06 inch wide), somewhat similar to horizon situation or a type of terrain avoidance display, was shown. A horizontal (0.02 inch wide) scribed line could be taken as representing an aircraft and the parallel cathode ray tube (CRT) displayed moving line as portraying a "horizon." Fore and aft control column movement would align the CRT moving line (hereafter called the vertical or vertically moving line) with the scribed line. A two-second time constant for delayed display-control feedback similar to that found in an aircraft was included, that is, the vertically moving line would not respond immediately to control action. Also similar to aircraft control systems was the relation between control column and display movement, i.e., forward column movement was necessary to bring the moving line up to the scribed line and vice versa.

Above the CRT display was a horizontal slot through which a visible (vertical) light beam was seen as moving left or right as the wheel was turned clockwise or counterclockwise, respectively (an analogous relationship would be driving to a point on the horizon). Ss were to try to keep the moving beam aligned with a scribed line in the middle of the display. As a control aid this display was color coded so that the light beam was red when gross errors occurred and green when errors were minor, with correct performance indicated when the beam was aligned with an etched line. The

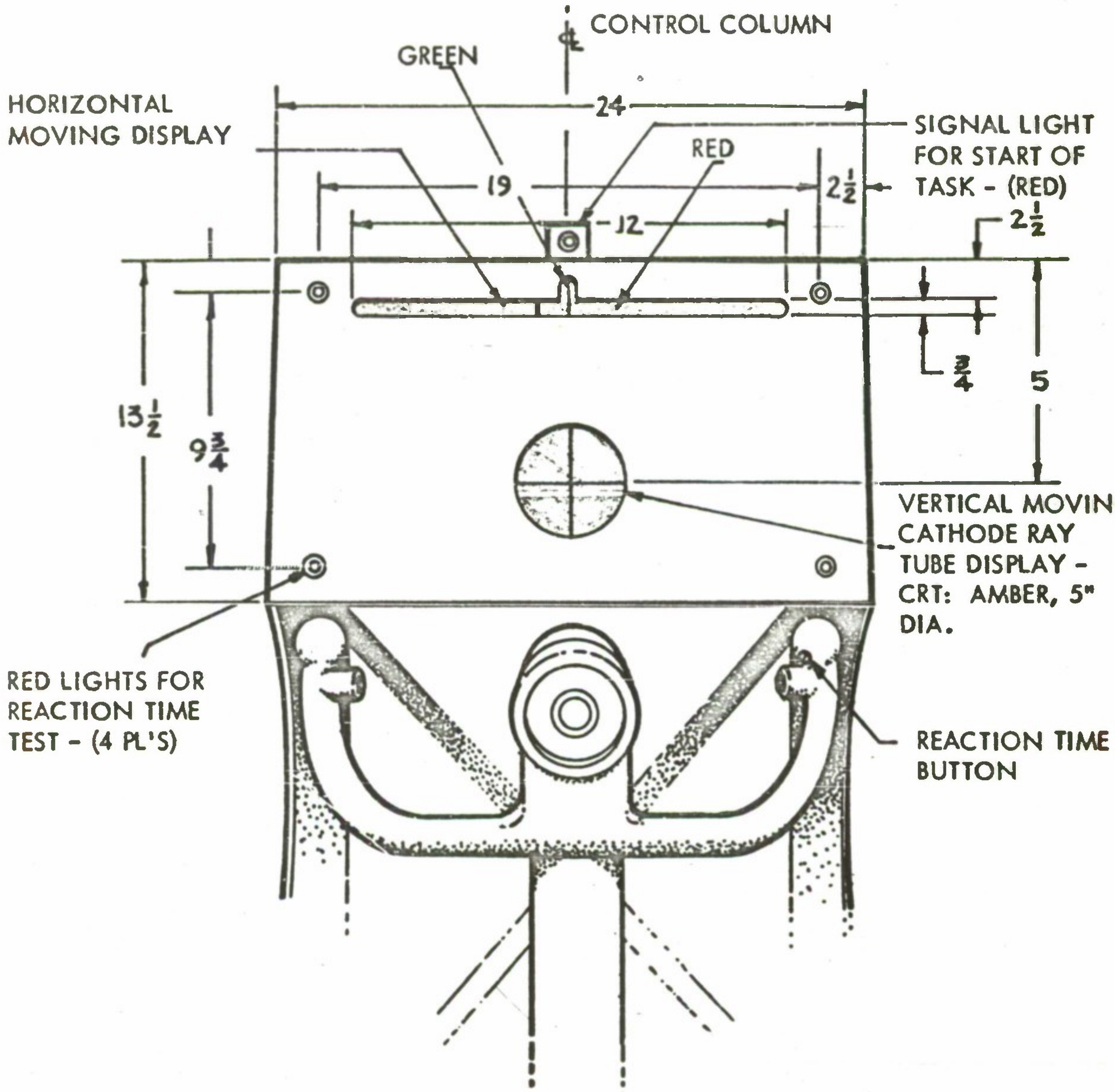


FIGURE 2

PANEL DISPLAY - CONTROL COLUMN ARRANGEMENT
(SUBJECT'S VIEW - NO SCALE)

green line was 0.2 inch wide compared to a 0.06 inch width for the light beam and a 0.03 inch wide, etched, vertical center line. Movement of the control wheel resulted directly in a damped movement of the light beam.

A signal generator was used to generate a sinusoidal display movement for the two moving displays. Although incorrect control movement could extend display movement, normal (programmed) variation was ± 1/2 inch at 4 cycles per minute (cpm) for the vertically moving display and ± 2 inches at 5 cpm for the horizontally moving display (figure 2). Maximum possible error count was 5472 for the former and 803 for the latter display. The different cpm for the two displays averted the possibility of synchronized control movement leading to correct performance on the two displays.

The two tracking tasks selected would permit some comparisons to determine whether performance problems could be varied or eliminated by design considerations. An additional measure, response time, could be obtained by the following organization: Four jeweled red lights, one-half inch in diameter and located in the corners of the display, were activated in a predetermined random order. Each light was activated twice during a test for eight reaction time measures per test. S̲ was instructed to turn each light off as it came on by pressing the right thumb button on the control wheel.

All responses to the displays were measured and recorded automatically. Tracking error was recorded as an integration (over time) of the difference between the desired position of the moving light beam and the actual position as controlled by S̲. Response to the lights was recorded simply as the interval of time each light was on.

The vibration used for this test was obtained by playback of specific four-minute samples of the taped records described earlier (page 8) and by sinusoidal vibration at 0.75 and 2.5 cps, defined by a signal generator. It was expected that the repetition of the four-minute sample would result in sufficiently valid data for this preliminary study and avoid extended test periods which were considered undesirable because of possible data confounding by fatigue. The repetitive four-minute sample also permitted a direct comparison between subjects under the same vibration condition.

Test Procedure

Instructions (Appendix A) were read, a medical examination was given, and ECG system contacts were attached prior to the test. S̲s proceeded to the vibration table where they were fastened to the seat with an aircraft lap belt and the ECG recording system was connected. S̲s were familiar with the general procedure and had considerable prior practice on the task.

The sequence of test conditions was as follows. A ten-second onset rate was used to bring S to the level of vibration for four-minute vibration tests with the same total time period used for nonvibration tests. A similar ten-second decrease was used at the end of each vibration period. The ten-second onset and other table adjustment times were absorbed in the rest period.

TABLE III

SEQUENCE OF EXPERIMENTAL CONDITIONS

	Test Conditions	Minutes		Test Conditions	Minutes
1.	Warm-up period	4	13.	Vibration test	4
2.	Rest period	2	14.	Rest period	2
3.	Nonvibration test	4	15.	Nonvibration test	4
4.	Rest period	2	16.	Rest period	2
5.	Vibration test	4	17.	Vibration test	4
6.	Rest period	2	18.	Rest period	2
7.	Nonvibration test	4	19.	Nonvibration test	4
8.	Rest period	2	20.	Rest period	2
9.	Vibration test	4	21.	Vibration test	4
10.	Rest period	10*	22.	Rest period	2
11.	Nonvibration test	4	23.	Nonvibration test	4
12.	Rest period	2	24.	End of session	

*To avoid excessive fatigue build up.

Ss were instructed to stretch and relax as completely as possible between tests. During the ten-minute rest period they were permitted to get out of the chair for seven minutes. They performed continuously with all displays during each test condition for a total of eleven test conditions per session (five with vibration, six without vibration). S were informed that any deviations of the displayed moving lines from the scribed lines would be counted as tracking errors. They were also told that the lights were to be turned off as soon as detected, with the time that the light was on being the performance measure.

After the test the post-vibration physical examination and an interview were completed. A summary of interview data is included on page 24.

RESULTS

Effects of vibration on performance for this test are indicated in the curves of figures 3 to 7. The data is plotted as a percentage figure with 0 representing no change in performance with vibration as compared to nonvibration testing, larger numbers indicating greater error and vice versa. The error percentage figure is based on the equation $V_2 = \frac{V_1 \pm V_3}{2}$ where V_1 is the nonvibration performance score obtained immediately before vibration; V_2 is the score obtained during the specified vibration; and V_3 is the nonvibration score obtained immediately after vibration. This formula, used for derivation of an error term, was employed for a specific reason. Measures from either or both nonvibration test conditions could have been considered representative of a proficiency level for any particular subject. However, the average of both appeared to be the best estimate since performance fluctuations were anticipated from such factors as test-to-test variability, learning and fatigue. Raw data converted to this figure is included in Appendix B.

Inspection of the curves will indicate possible trends which one might consider sufficient for valid conclusions. However, the differences between Ss could suggest many different and often opposed or misleading conclusions. The logic of statistical reasoning has been employed to provide guidance in determining which variations are possibly caused by chance and subject variability and which variations are most likely due to some difference between test conditions. The results of this analysis are shown in Table III. For this study the five per cent (.05) level of significance was considered a sufficient test level for statistical determination of factors attributable to chance. That is, when the probability was that a difference or change may occur by chance five times or less in a hundred, it was accepted that the change was due to the experimental conditions. In the tables this level is represented by one asterisk, with double and triple asterisks representing the .01 and .001 levels, respectively.

Since the tests were intended to determine whether performance correlations between types of vibration exist, only those statistical comparisons are described here and comparisons with nonvibration performance is omitted. In keeping with the analysis of variance procedure for the Latin Square design, the first comparison determined whether a difference existed which was due to (1) order (or sequence), (2) subjects, or (3) the experimental variable (types of variation or vibration conditions). "Order" (1) of test conditions was not significant, so one of the possible confounding factors was greatly reduced and variability between (2) subjects and (3) conditions could be attributed to these two variables (2 and 3) and their interactions within this framework. It will be noted that a performance difference between experimental vibration conditions was found for the vertically moving tracking task only (Table III) with no changes indicated for the horizontally moving tracking task or in response time for the signal light program.

Another statistic (Tukey's gap test, reference d) was used to determine which experimental conditions could be causing the differences resulting in significant differences between vibration effects on performance. This test indicated that 2.5 cps, 1.08 inches double amplitude (DA), and 0.75 cps, 1.57 inches double amplitude performance data were significantly different with performance poorer for the first and better for the latter when both were compared to performance on other experimental conditions. A borderline case toward better performance was suggested for 2.5 cps, 0.26 inches DA, although students' t tests indicated that no particular difference existed at this point. This was taken as indicating that no real difference occurred for the condition.

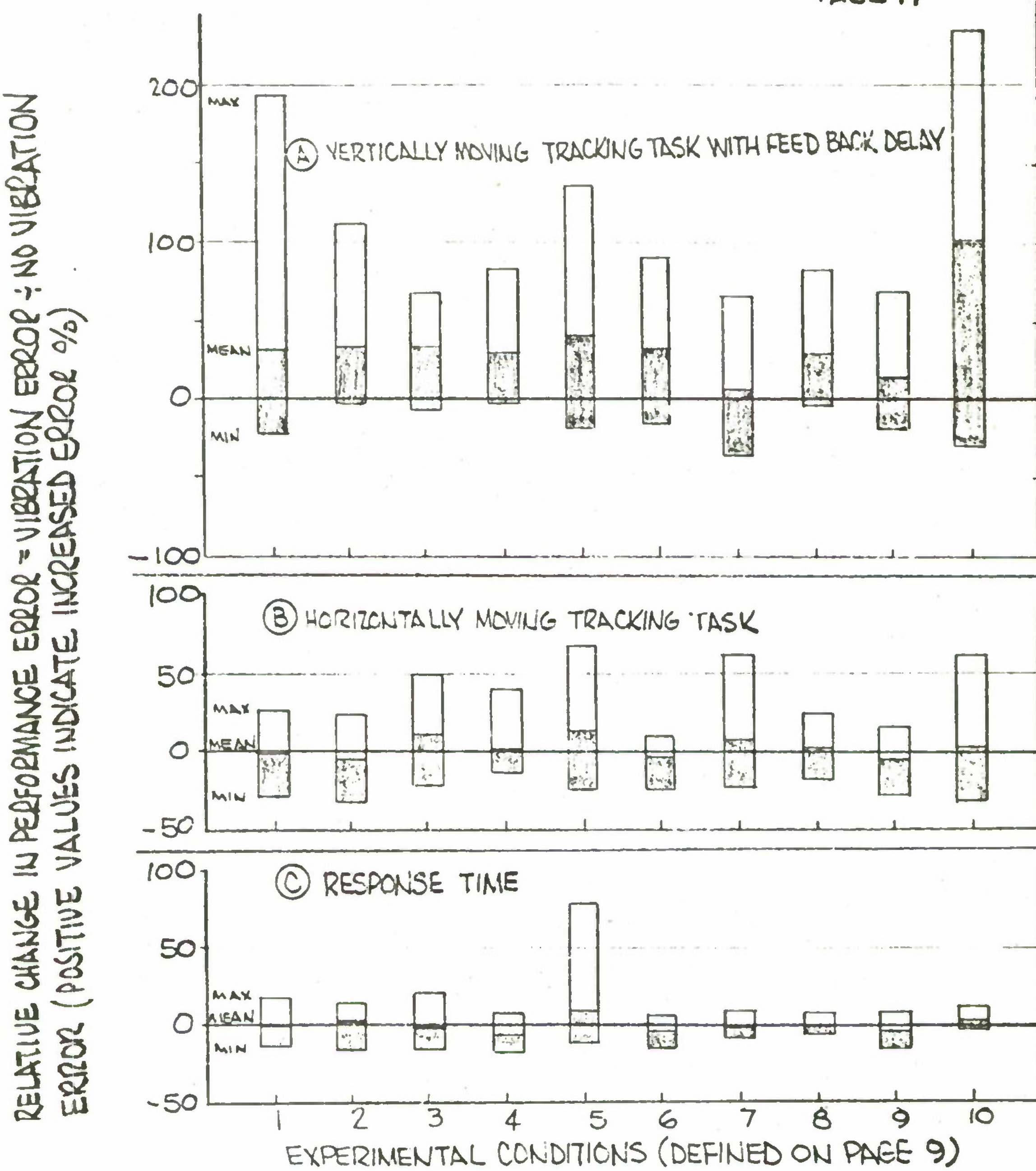
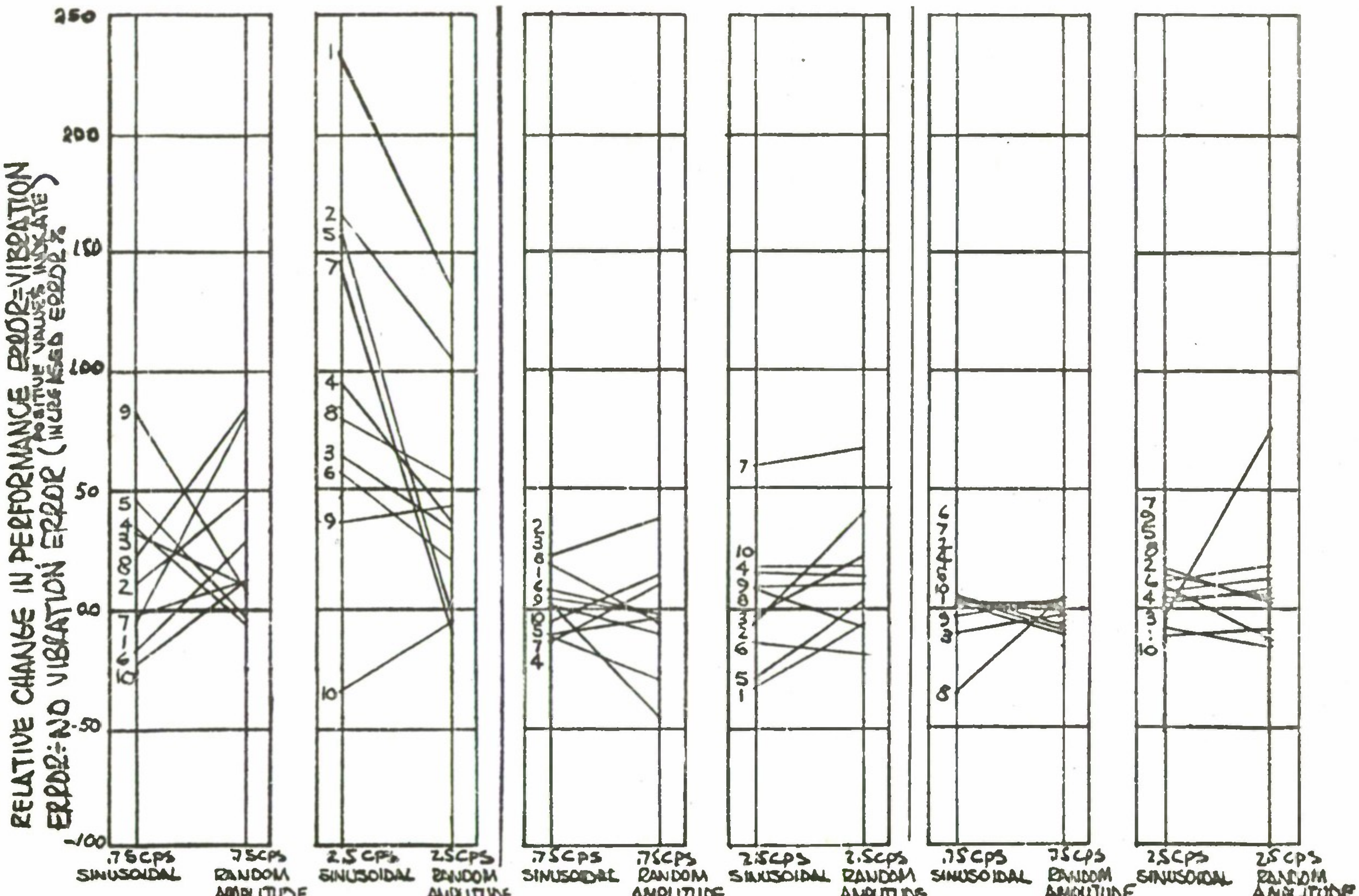


FIGURE 3 , SUMMARY OF RELATIVE CHANGE IN PERFORMANCE FOR THE DIFFERENT VIBRATION TEST CONDITIONS OF THIS EXPERIMENT. MEAN AND RANGE (MAX. AND MIN.) OF PERFORMANCE ON EACH DISPLAY ARE INDICATED FOR EACH TEST CONDITION. THE LINE SEPARATING SHADED AND OPEN AREAS INDICATES THE MEAN. (DATA IS TABULATED IN APPENDIX B)



Ⓐ VERTICALLY MOVING TRACKING TASK WITH DELAYED FEEDBACK

Ⓑ HORIZONTALLY MOVING TRACKING TASK

Ⓒ RESPONSE TIME

FIGURE 4 : PERFORMANCE COMPARISONS FOR VIBRATION CONDITIONS WITH APPROXIMATELY EQUAL MEAN AMPLITUDE. NUMBERS ON THE GRAPH REPRESENTS SUBJECTS, FROM APPENDIX B

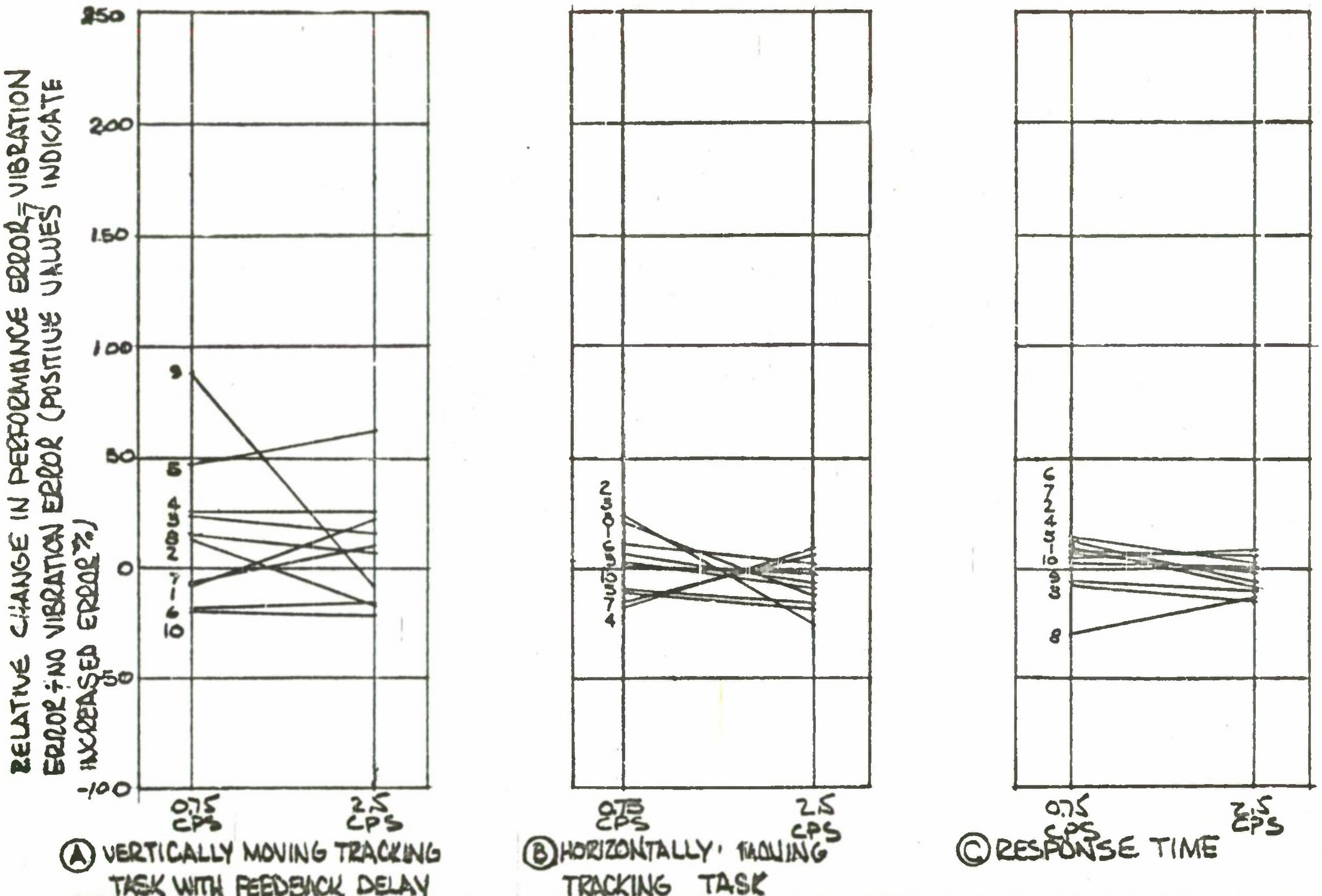


FIGURE 5 : PERFORMANCE COMPARISON FOR SINUSODIAL VIBRATION CONDITIONS JUDGED APPROXIMATELY EQUAL (CONDITIONS 8,10; NUMBERS ON GRAPH IDENTIFY SUBJECTS)

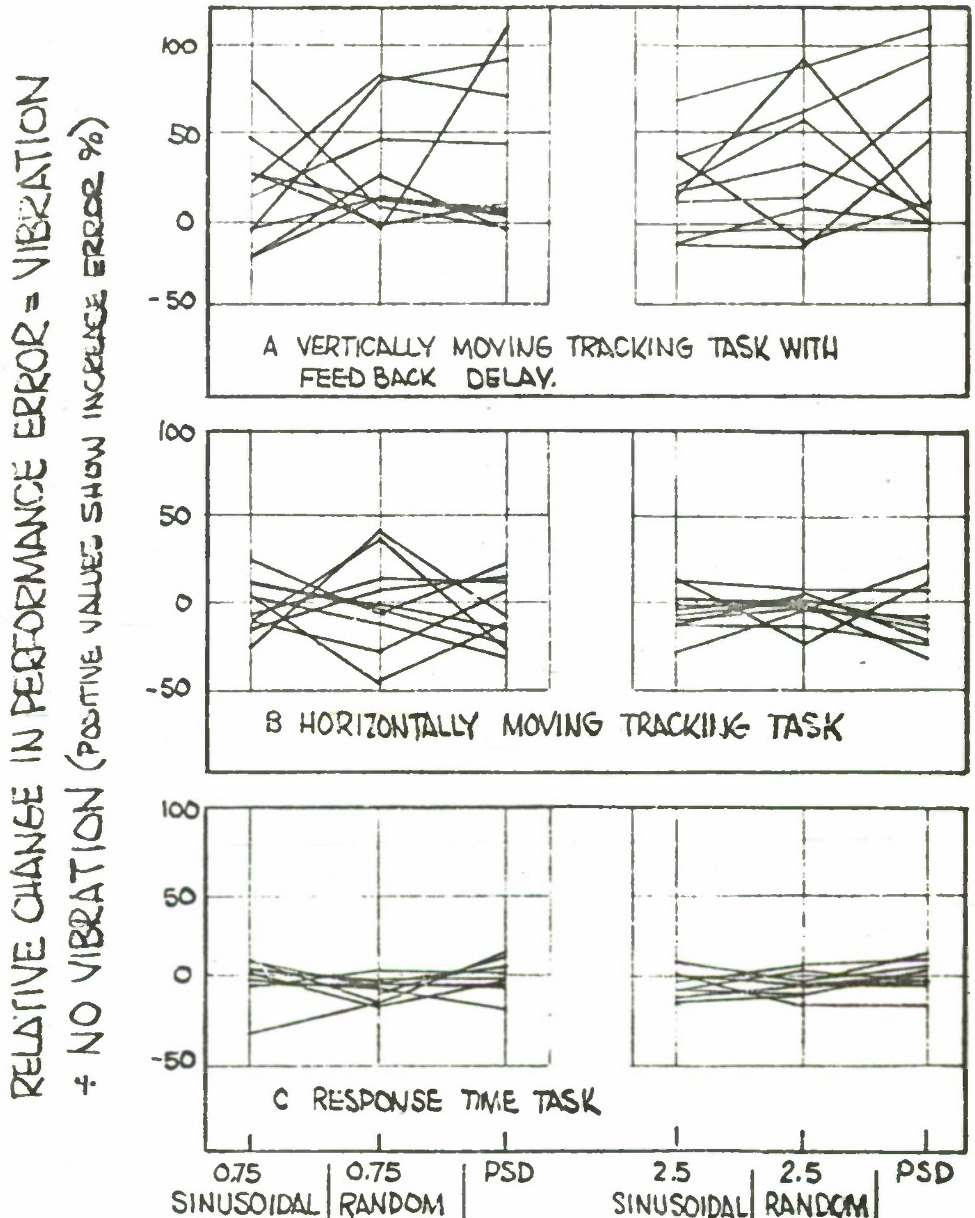


FIGURE 6 : A COMPARISON OF TASK PERFORMANCE FOR VIBRATION CONDITIONS WITH APPROXIMATELY EQUAL RMS AMPLITUDE POWER.

(TEST CONDITIONS 2,3,4,6,8 & 9; EACH LINE REPRESENTS ONE SUBJECT)

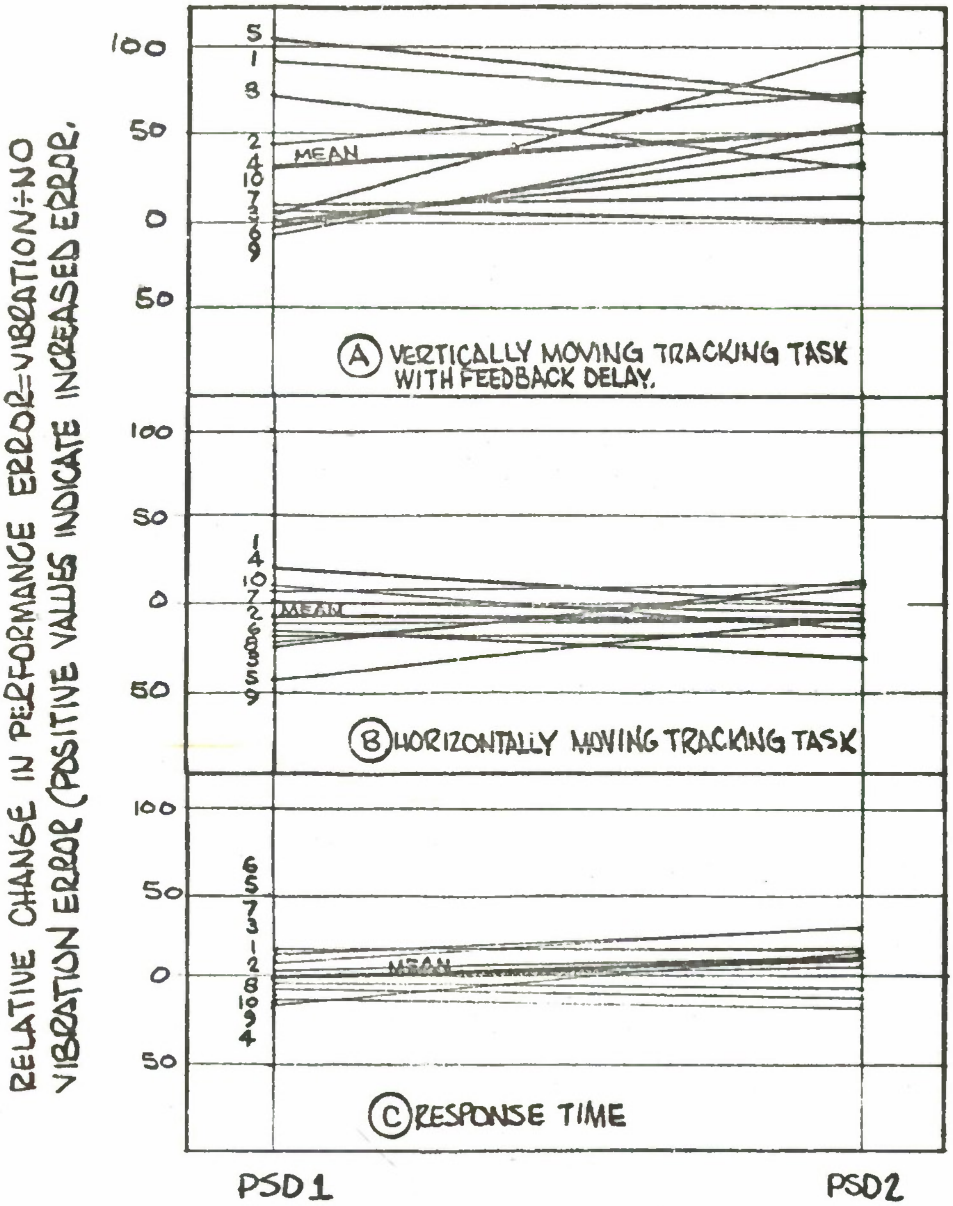


FIGURE 7 : A COMPARISON OF TASK PERFORMANCE WITH DIFFERENT PSD APPROXIMATIONS. DATA IS PRESENTED FOR MEAN, RANGE & INDIVIDUAL PERFORMANCE ERROR. NUMBERS REPRESENT SUBJECTS FROM APPENDIX B.

TABLE IV

RESULTS OF STATISTICAL ANALYSIS (ANALYSIS OF VARIANCE)

A. VERTICALLY MOVING DISPLAY

Source of Variation	Degrees of Freedom	Sum of Squares	Mean of Squares	F Variance Ratio	Significance
Order or Test Sequence	9	1.667	.185	1.29	--
Subjects	9	6.472	.719	5.02	.001
Experimental Variable (or Vibration Condition)	9	6.243	.694	4.84	.001
Residual	72	10.322	.143		
Total	99	24.704			

B. HORIZONTALLY MOVING DISPLAY

Source of Variation	Degrees of Freedom	Sum of Squares	Mean of Squares	F Variance Ratio	Significance
Order or Test Sequence	9	0.547	.061	1.82	--
Subjects	9	0.820	.091	2.73	.05
Experimental Variable (or Vibration Condition)	9	0.344	.038	1.14	--
Residual	72	2.408	.033		
Total	99	4.119			

C. RESPONSE TIME TEST

Source of Variation	Degrees of Freedom	Sum of Squares	Mean of Squares	F Variance Ratio	Significance
Order or Test Sequence	9	0.0589	.0065	.478	--
Subjects	9	0.1303	.0145	1.007	--
Experimental Variable (or Vibration Condition)	9	0.1554	.0173	1.272	--
Residual	72	0.9871	.0136		
Total	99	1.3227			

Subject Reports

In general, S s indicated that they noticed little or no effect on performance. The general consensus was that any effect which might exist would be for 2.5 period random amplitude with a mean displacement of 1.08 inches. However, subjects did not believe difference in performance occurred. The 2.5 cps, 1.08 inches constant amplitude was generally agreed to affect comfort most, being the least comfortable of the conditions although it was not felt to affect performance. The difference in subject opinion for performance and judgment appears to be summarized by one S's comment that "you tend to get out of phase with the random vibration, making it more difficult to maintain consistent performance." Even in this case, however, the subject did not feel that performance would be significantly different. PSD was apparently considered fairly comfortable with no one selecting it as most affecting comfort or performance.

S s felt that vibration "made the task easier" with one major effect being a tendency to increase alertness to the task requirements. However, one S commented that random vibration tended to distract him because "phasing in" with the vibration was more difficult. He felt he could adapt to the regularity of sinusoidal frequencies with a smaller net effect on performance.

DISCUSSION

Vibration of the human presents two major design problems, assuming that vibration severity does not endanger the operator because of loss of control, physiological and psychological stress, etc. Design engineers need to know how vibration affects human performance and how it will be affected in a specific, randomly vibrating system. Since all specific vibration environments cannot be predicted for human vibration testing, knowledge of human performance correlations, or transfer functions, may permit prediction of performance in the new system.

This exploratory study was designed to investigate performance with the two types of vertical vibration (sinusoidal and random) for possible performance correlations, and to determine feasibility of conversion factors for relating and predicting performance from one vibration condition to the other. If likely relationships were indicated, further research might indicate more exact conversion factors and available data could be applied directly in design efforts. Sinusoidal vibration could then be used exclusively to further define effects of vibration on human performance for application to operational situations.

For the feasibility exploration to be conducted in this study several descriptions of vibration were used, from systematically derived judgment of intensity (reference a) to the structural dynamics concept of RMS power. This method permitted comparisons of performance with sinusoidal versus random vibration as desired and between sinusoidal conditions relative to other hypotheses, such as judgment of vibration being related to performance.

Only one subtask of the three was found to be differently affected by different vibration conditions. Performance on the vertically moving tracking task with control-display feedback delay was significantly degraded by 2.5 cps, 1.08 inches double amplitude vibration. The horizontally moving tracking task without feedback delay and the response time task were unchanged from one condition to another--evidence of the importance of display-control selection in design. This suggests that a universal transfer function may not be required since some tasks may not be affected by vibration.

The comparisons which were the design purpose of this experiment can be made for the one task which vibration was known to affect from preliminary testing and which was affected differently by the vibration conditions of this test. Performance difference from other test conditions for the 2.5 cps, 1.08 inches DA condition eliminates judgment as a potential basis for performance comparisons, since this condition and 0.75 cps, 9.04 inches had been defined as "extremely annoying" from an earlier experiment. For the same reason, any relationship for random amplitude, PSD, and sinusoidal vibration is rejected.

Of those comparisons made in this experiment (illustrated in figures 3 to 7), only RMS amplitude power could be indicated as a parameter leading to comparable data since the equal RMS condition was not involved in the 2.5 cycle condition for which performance was different. As indicated in figure 6, sinusoidal and constant period random amplitude vibration, RMS amplitude power equal to the RMS amplitude power for the PSD, could be associated with equivalent effects on performance.

In other words, performance with the PSD vibration condition did not vary considerably from performance with 0.75 cps and 2.5 cps conditions, with amplitude power equated to the PSD content for these frequencies. The data indicates that an RMS for 2.5 cps (sinusoidal) which is equal to the RMS amplitude power for the 2.5 cycle portion of the PSD results in comparable performance, with similar results for 0.75 cps. Also, no particular difference in performance exists between 0.75 cps (1.7 RMS) and 2.5 cps (0.09 RMS) amplitude power. This leads to the suggestion that the key to a transfer function is some combination of frequency and a factor related to RMS.

The latter comparison leads to a more general question which cannot be answered without more extensive data. It is not clear why a relatively small difference in error is found when the sinusoidal vibration performance is compared to performance with the PSD since the latter includes the full additive component of both 0.75 and 2.5 cps measured sinusoidal conditions tested. Some type of algebraic additive relationship appears likely, such as (a) (0.75 cps) ± (b) (2.5 cps) performance = PSD performance.

Lack of variation related to widely differing amplitudes with the same frequencies suggests that relatively no differential change in performance occurs as a function of frequency within the amplitude ranges used in this study. This suggests a possible relation to acceleration forces which vary with frequency and amplitude, but no clear-cut distinction could be drawn. Tests are necessary wherein acceleration is constant for distinct performance measures at different frequencies (possibly using more precise performance measures subject to less individual variability) before a clear answer can be derived. If one is to test acceleration as a factor, the areas of body sensitivity must also be considered. It is suspected that establishing a strong relation will still be difficult to accomplish since discomfort would undoubtedly result in data confounding. A systematic relationship could confuse attempts to derive transfer functions.

In summary, there is evidence that a transfer function can be found and that data derived with sinusoidal data may be extended to complex patterns of random vibration. It appears that usable transfer functions can be attached to mechanical descriptions of vibration without a complete understanding of all effects on human operators. Results of this experiment show that the physical description which could serve this purpose may be a combination of frequency and some factor related to RMS.

More data and analysis is required to examine the tendency for a slight increase in certain tracking errors related to specific vibration conditions. In figure 3 (A, B & C) it can be seen that condition 5 (2.5 period random amplitude, 2.16 inches DA) is associated with a tendency to greater error. This appears to be influenced by individual deviation, but may be related to a real effect of the condition on performance which cannot be detected because of wide individual variability. In figure 3a, experimental conditions 3, 5, 7 and 10 suggest the possibility of some similar unidentified factor. Again, it may be simply a function of individual variability. The plot certainly suggests that further study with these conditions is warranted using tasks less subject to individual variability as indicated earlier, even though there was no statistical indication of differences associated with these conditions in this experiment.

It must be recognized that other displays or vibration conditions may cause the results to differ significantly from those obtained in this test. One must also bear in mind the possibility that more severe vibration intensities or longer exposure time may change some of the observations and comments herein which are based on this data. Although considerable difference in performance was found between subjects the issue was considered minor, relative to the purpose of this test, that is, "Is there a common physical parameter of vibration by which different types of vibration can be considered to have an equivalent effect on performance?" The pertinence of the assumption is obvious with the wide range of operator variability which any vehicle designer must consider (and the requirement to design for a broad range of unique individual capabilities). Also, it is desirable to reiterate the ground rules for this experiment--that the emphasis is on exploration to discover trends toward a transfer function rather than necessarily precise and final answers.

APPENDIX A

INSTRUCTIONS

Subject

Emphasis is on performance for this portion of the vibration study. Your job will be to operate the displays that you became familiar with during the first experiment. You will be expected to keep the vertical and horizontal moving lines aligned, or track them.

The lights in the corners of the display will come on at random intervals. When this happens, you are to continue tracking but press the button to turn the light off as soon as you see it. Release the button as soon as the light goes off, and do not press it until you see the next light.

It is essential that you perform at your best on all displays concurrently. Rest periods are purposely scheduled into the sequence to permit you to relax and prepare for the next test run for the day.

You are asked to avoid any discussion of this test until after the full experiment is completed for two reasons: (1) other studies have shown that such discussion can completely change the data; (2) the data to be collected is rather sensitive to changes in viewpoint. We would like your attitude toward the test to remain as nearly the same as possible throughout the experiment.

Are there any questions?

Procedural Instructions:

A. The red light mounted on top of the panel display will go off when the error count starts. This will be a signal for you to start performing. (Items 1, 2 and 3 are for vibration only.) The sequence leading up to this is as follows:

1. The seat will be raised to the center of the stroke.

2. Final equipment settings will be completed.

3. A 10 second onset rate will be initiated to bring you to the right level of vibration for the test.

4. The red light will go off, you are to start performing, and the error count will start.

5. Errors will be counted for any deviation from the scribed lines. Additional cues on the display are to help you maintain alignment.

6. The horizontal moving line has a fairly direct relation to control movement. The vertical moving line has a two-second delay between control movement and display response.

B. Each vibration period is scheduled to last four minutes.

C. Are there any questions?

D. Should you want to stop vibration at any time release the cutoff switch.

APPENDIX B

INDIVIDUAL DATA FOR THE TEST

Entries indicate relative error performance error = vibration performance ÷ nonvibration performance error.

SUBJECT	EXPERIMENTAL CONDITION 1	2	3	4	5	6	7	8	9	10
1	2.9338	1.9375	1.5531	1.8117	2.3627	1.6353	1.5858	0.9616	1.3316	3.3538
2	0.7785	1.4333	1.1312	1.4743	2.0261	0.8400	0.6595	1.1743	0.8707	2.7069
3	1.5671	1.0065	1.3964	1.1133	1.3542	1.5895	1.1267	1.2827	1.2036	1.6478
4	1.1266	1.1016	1.6111	0.9972	1.4013	0.8801	1.1301	1.2876	1.3761	1.9943
5	1.4706	2.1121	1.0027	0.9713	1.0039	1.8955	1.0073	1.4832	1.6933	2.5968
6	1.0518	0.9668	1.0172	1.2714	1.1934	1.0828	1.0192	0.8152	0.8754	1.5954
7	1.1128	1.0540	1.6848	1.1507	0.8080	1.9021	0.6378	0.9713	1.1582	2.4935
8	1.0693	1.7003	1.3445	1.8333	1.5182	1.1332	1.6654	1.2494	1.1053	1.8512
9	0.8722	0.9612	1.6239	1.1143	1.4325	0.9494	1.0048	1.8303	0.9343	1.3468
10	1.0919	1.0788	0.9276	1.1397	0.9185	1.3205	0.7762	0.3071	0.8067	0.6915
Mean (Col)	1.3075	1.3352	1.3292	1.2877	1.4019	1.3219	1.0613	1.1863	1.1355	2.0278
Mean (Row)	1.9467	1.3095	1.3288	1.2906	1.5237	1.0888	1.2973	1.4470	1.2061	0.9559
Mean (g)			.13	.26	.33	.083	.13	.26	.083	.33

1. ½ Amplitude PSD
2. Full Power PSD
3. 0.75 Period 4.26" DA Random Amplitude
4. 0.75 Period Random Amplitude, 1.7 RMS, 9.04"
5. 2.5 Period Random Amplitude, 2.16"
6. 2.5 Period .09 RMS Random Amplitude
7. 0.75 cps 1.57" DA
8. 0.75 cps 1.6 RMS 4.52" DA
9. 2.5 cps .09 RMS .26" DA
10. 2.5 cps 1.08" DA

Table III. Performance with the Vertically Moving Tracking Task, Rearranged from the Latin Square so that Each Column Entry Represents Relative Performance for a Particular Condition, Indicated by the Column Heading.

SUBJECT	EXPERIMENTAL CONDITION 1	2	3	4	5	6	7	8	9	10
1	0.9538	0.7882	1.0744	0.9742	0.9255	1.0419	1.3562	1.0756	0.9778	0.6917
2	1.1143	0.9057	1.1020	1.3846	1.4023	0.9669	0.7714	1.2475	0.7222	0.9630
3	0.9167	1.2308	1.2632	0.9302	1.2034	0.9778	1.0619	1.2250	0.8824	0.9787
4	1.0505	1.1429	1.0759	1.0753	1.1258	0.7677	0.9504	0.8298	1.1448	1.1375
5	1.0781	0.7440	1.0789	1.3982	1.0365	0.8394	1.1200	0.8939	0.8684	0.6977
6	0.8293	0.8977	0.7838	0.5455	0.7640	1.0388	0.8235	1.0280	0.9157	0.8824
7	0.9202	1.0880	1.4862	0.7193	1.6786	1.0962	1.6106	0.8831	1.1351	1.6182
8	0.7107	0.8687	0.8613	0.9829	0.9273	0.9811	1.0600	1.1232	1.0780	1.0774
9	1.2552	0.6818	1.0909	0.8721	1.0853	0.9863	1.0000	1.0141	0.9857	1.1231
10	1.0484	1.1270	1.2558	1.1329	1.1484	1.0759	0.9487	0.9231	0.8788	1.1429
Mean (Col)	0.9877	0.9475	1.1073	1.0015	1.1297	0.9772	1.0703	1.0243	0.9589	1.0312
Mean (Row)	0.9859	1.0580	1.0670	1.0300	0.9755	0.8509	1.2236	0.9671	1.0094	1.0682
Mean (g)			.13	.26	.33	.083	.13	.26	.083	.33

1. $\frac{1}{2}$ Amplitude PSD
2. Full Power PSD
3. 0.75 Period 4.26" DA Random Amplitude
4. 0.75 Period Random Amplitude, 1.7 RMS, 9.04"
5. 2.5 Period Random Amplitude, 2.16"
6. 2.5 Period .09 RMS Random Amplitude
7. 0.75 cps 1.57" DA
8. 0.75 cps 1.6 RMS 4.52" DA
9. 2.5 cps .09 RMS .26" DA
10. 2.5 cps 1.08" DA

Table IV. Relative Performance with the Horizontally Moving Tracking Task, Rearranged from the Latin Square so that Each Column Entry Represents Performance During a Particular Condition, Indicated by the Column Heading. (Entries are relative to nonvibration performance.)

SUBJECT	EXPERIMENTAL CONDITION 1	2	3	4	5	6	7	8	9	10
1	0.9416	1.0000	0.8647	0.8173	0.8734	0.9571	1.0746	1.0157	1.0882	0.9758
2	0.8555	1.0000	0.8320	0.9922	1.0583	0.8923	0.9722	1.0564	0.9279	1.0190
3	0.9804	1.0258	0.9970	1.0687	1.7736	0.8800	0.9431	0.9462	0.8500	0.9889
4	1.0537	0.8259	0.9744	0.9369	1.0625	0.8430	1.0159	1.0512	1.0154	1.0099
5	0.9967	1.1094	1.2068	0.9030	1.1890	1.0424	0.9732	1.0510	0.9835	1.0717
6	0.9921	1.1358	0.9187	0.8527	1.0476	0.9960	0.9746	1.0788	1.0079	1.0118
7	0.9953	1.0653	0.9091	0.9684	1.0286	1.0198	0.9091	1.0769	0.9583	1.1200
8	0.9138	0.9913	1.0642	0.8408	0.8770	0.9561	1.0806	0.6934	0.8824	1.0308
9	1.1619	0.9352	1.0598	0.9634	1.0291	1.0535	0.9706	0.9709	0.9100	1.0874
10	1.0000	0.9746	1.0172	0.9789	0.8945	0.9417	0.9450	1.0175	1.0041	0.9675
Mean (Col)	0.9921	1.0063	0.9844	0.9323	1.0834	0.9582	0.9859	0.9958	0.9628	1.0283
Mean (Row)	0.9609	0.9636	1.0454	0.9789	1.0527	1.0016	1.0051	0.9330	1.0142	0.9741
Mean (g)			.13	.26	.33	.083	.13	.26	.083	.33

1. ½ Amplitude PSD
2. Full Power PSD
3. 0.75 Period 426" DA Random Amplitude
4. 0.75 Period Random Amplitude, 1.7 RMS, 9.04"
5. 2.5 Period Random Amplitude, 2.16"
6. 2.5 Period .09 RMS Random Amplitude
7. 0.75 cps 1.57" DA
8. 0.75 cps 1.6 RMS 4.52" DA
9. 2.5 cps .09 RMS .26" DA
10. 2.5 cps 1.08" DA

Table V. Relative Performance on the Response Time Task, Rearranged from the Latin Square so that Each Column Entry Represents Performance for a Particular Condition, Indicated by the Column Heading. (Entries are relative to nonvibration performance.)

SUBJECT	VERTICALLY MOVING DISPLAY	HORIZONTALLY MOVING DISPLAY	RESPONSE TIME
1	1.74	0.0	1.25
2	1.77	0.926	1.06
3	1.435	1.11	1.055
4	1.247	0.919	1.06
5	1.704	1.13	1.18
6	1.44	0.73	1.08
7	1.96	0.985	1.18
8	1.38	0.872	0.945
9	1.542	0.995	0.992
10	1.014	1.122	0.993

TABLE VI. PERFORMANCE ON TASKS USED IN THIS TEST WITH THE SECOND PSD APPROXIMATION

ACKNOWLEDGEMENT

Cooperation of the following individuals, who served as subjects for this experiment, was appreciated.

M. E. Arnold
J. K. Davis
W. D. Fagan
G. D. Goodwin
D. M. Heller
A. E. Lee
A. D. Ogle
O. Praeger
A. A. Sullivan
R. G. Thomas